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IMPACT OF GOCE ON THE NORDIC GRAVITY FIELD MODELLING

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ABSTRACT

GOCE level-2 Tzz and Txx gravity gradients at satellite altitude are used in combination as input data to predict surface free air gravity anomalies over the Nordic region using Least Square Collocation. We test the performance of using covariance functions created separately from Tzz gradients and surface free air gravity anomalies to predict terrestrial gravity anomalies with a direct comparison of 19 mgal level and much better (7-8 mgal) when surface data are filtered at the GOCE resolution. We found that the results are slightly dependent of covariance function. Combined with DTU10 Mean Sea Surface model, both the NKG-2004 quasi-geoid model of the Nordic and Baltic Area and the one obtained using second generation GOCE spherical harmonic coefficients based on time-wise method can successfully reproduce the higher level of the Baltic Sea relative to the Atlantic Ocean.

Key words: GOCE TRF gradients, Least squares collocation, quasi-geoid, mean dynamic topography.

1. INTRODUCTION

The GOCE satellite (Gravity Field and Steady-state Ocean Circulation Explorer) [2] was successfully launched on 17 March 2009. The GOCE satellite observes gravity gradients in space with accelerometers over short baselines within a platform flying in drag-free mode. GOCE is the first satellite mission that observes direct functionals of the Earth gravity field from space. With GOCE, the determination of a gravimetric geoid at 1 cm level accuracy is expected at wavelengths of a few hundred km and longer, leaving out variability in the order of 20-30 cm r.m.s for typical regions due to short-wavelength gravity field variations. Therefore, there is a need to continue to use terrestrial or airborne gravity measurements to complement the GOCE observations.

Furthermore, GOCE observations can potentially be used to predict surface gravity anomalies in unsurveyed areas of the Earth, in mountains, where gravity usually collected only along the roads in valleys and over the oceans where satellite altimetry derived gravity anomalies are polluted due to not precisely known ocean circulation or sea-surface topography variations [10]. Regions with a good coverage of surface data can be used to test the utilization of GOCE for these purposes. The Nordic area is prime candidate for such a test area with its dense surface gravity measurements and relatively well known a 35–40 cm mean sea surface topography difference between the northern Baltic Sea and the North Sea due to the large river input and resulting salinity gradient [3].

The first objective of this paper to compare the performance of using covariance functions created separately from Tzz gradients and terrestrial gravity anomalies to predict terrestrial gravity anomalies. The second objective is to investigate whether quasi-geoid derived from GOCE spherical harmonic (SH) coefficients make any improvements over the NKG-2004 quasi-geoid model of the Nordic and Baltic Area [6] as well as to Mean Dynamic Topography model of the Baltic Sea.

2. DATA

2.1. GOCE

The GOCE High level Processing Facility (HPF) is responsible for delivering the level 2 global gravity model from which geoid heights can be determined [8]. Within the HPF three processing strategies have been adopted to obtain SH coefficients from GOCE data. In this study, we use second generation GOCE SH coefficients up to degrre and order 250 based on the time-wise method [9] developed using 8 months of GOCE data, November 2009 to July 2010.

To predict surface gravity anomalies we use the GOCE level-2 gravity gradient data in the Terrestrial Reference Frame (TRF) covering a period of two years, 2009-2010. GOCE TRF gradient data are obtained from the GOCE Virtual Online Archive. We use gravity gradients in good quality taking into account flags for outliers. We select Tzz and Txx gravity gradients at 0.15^{o} x 0.20^{o} resolution (pixel binning to approx. 12 km resolution depending on latitude) at a slightly higher resolution than the selected surface gravity anomalies in the region (see section 2.2 for details).

The Mean Dynamic Topography (MDT) models are calculated by subtracting the quasi-geoid heights from

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DTU10 mean sea surface (MSS) model [1] at 2 minute resolution by using the GOCE User Toolbox (GUT) version 1.1 (http://earth.esa.int/gut/). The MSS model is converted to same tide system and same reference ellipsoid as the quasi-geoid models.

2.2. Surface Gravity Anomalies

Surface free air gravity anomalies are selected from NKG gravity database at 0.173° x 0.25° resolution in the borders of 54.1°- 71.9° N and 4.1° to 31.9° E. A total of 10861 free-air gravity anomaly measurements are selected, see Tab.1 for statistics.

Table 1. Statistics of free-air gravity anomalies from terrestrial observations, LSC predictions using two different covariance functions, from second generation GOCE SH coefficients (M=250) based on time-wise (TIM) method.

unit : mgal	mean	std.	min.	max.
Terrestiral observations	-1.1	26.9	-122.6	183.1
LSC predicted (covariance from surface free air gravity anomalies)	0.8	20.2	-63.3	78.7
LSC predicted (covariance from GOCE Tzz gradient anomalies)	0.8	20.1	-61.7	77.4
GOCE TIM SH coefficients (M=250)	0.6	21.8	-89.5	85.5

3. METHODOLOGY AND RESULTS

GOCE gravity gradients can be used as data in the Least Squares Collocation (LSC) method where each observation, regardless of the data type, is treated as the value of a functional applied on the anomalous potential, and some optimal "smooth" least norm approximation is constructed in accordance with the observed functional values in a way that the approximation is a harmonic function [5]. This approximation may subsequently be used for the estimation of all the gravity field components and their standard error needed for geodetic applications, such as geoid heights [11].

LSC may also take into account data located at different altitudes through the use of a spatial covariance function. The applied covariance model implies that the associated approximation to the anomalous gravity potential is harmonic down to the so called Bjerhammar sphere, with radius R_B smaller than the mean Earth radius.

We determined covariance functions separately from GOCE Tzz gradients and terrestrial free air gravity anomalies. The data for the use in covariance function estimation and the onward collocation step is required to be smooth with small variance and have a good statistical distribution in order to properly interpret the error-estimates. To achieve the goal of smoothing and permit the use of spherical approximation in LSC we reduced the surface gravity anomalies, GOCE Tzz and Txx gravity gradient anomalies for EGM08 up to degree and order 60.

We used Tzz and Txx components in combination as input data to LSC to determine the GOCE estimated surface free air gravity anomalies. We further compare the results of the prediction using LSC with corresponding results of the computation of the gravity anomalies using second generation GOCE SH model based on time-wise method [9].

Empirical covariance functions are determined and then fitted to a pre-selected model covariance functions of Tscherning-Rapp model [12].

The residual free air gravity anomalies are determined by LSC, where the required auto and cross-covariance functions are computed by covariance propagation from the analytically modeled local covariance function (Eq.1).

$$\operatorname{cov}(T_P, T_Q) = a\sum_{i=2}^{N}\left[\frac{a^2}{r_P r_Q}\right]^{i+1}\sigma_i^2 P_i(\cos\psi) + \sum_{i=N+1}^{N}\left[\frac{R_B^2}{r_P r_Q}\right]^{i+1}\frac{A}{(i-1)(i-2)(i+4)}P_i(\cos\psi) \tag{1}$$

where, P and Q are two points having a spherical distance ψ and r_P, r_Q are the distances of two points from the origin, R_B is the radius of Bjerhammar sphere and σ_i the error degree-variance. The covariance parameters a (scale parameter), A and the Bjerhammar radius R_B are determined using an iterative non-linear adjustment [7].

The covariance function (Fig.1) parameters determined by reduced surface free air gravity anomalies and reduced GOCE Tzz gradient anomalies are shown in Tab.2.

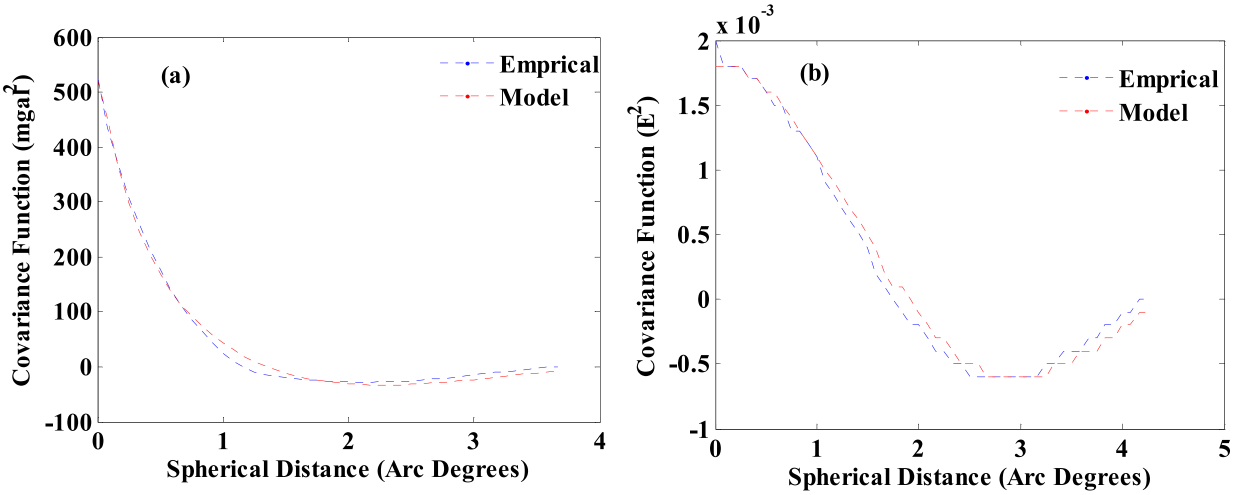

Figure 1. Signal empirical (blue) and model (red) regional covariance functions (a) from surface gravity anomalies (b) from GOCE Txx gradients in the Nordic region after the removal of the contribution of EGM08 to degree 60.

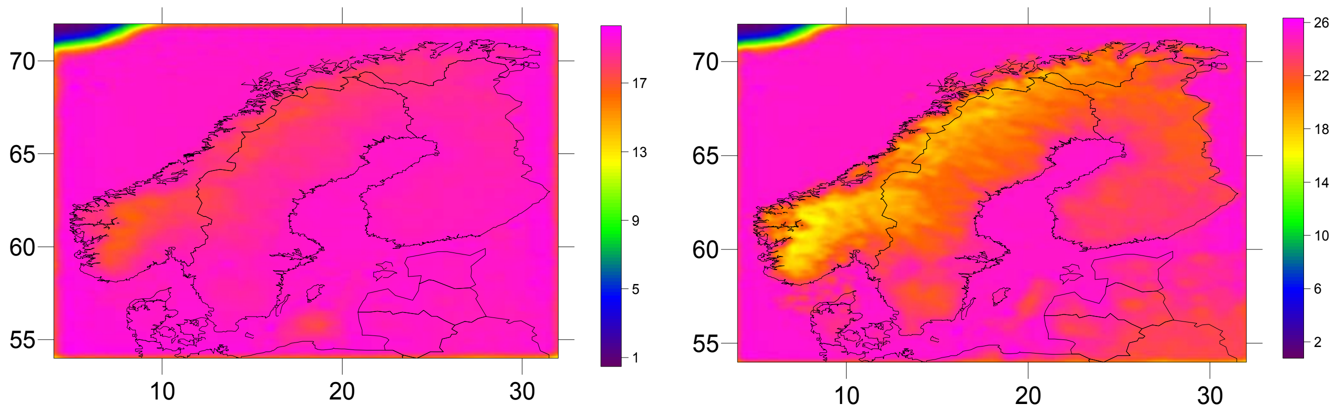

Figure 2. The error estimation (mgal) of the predicted reduced free air gravity anomalies from LSC method using two different covariance functions from (a) terrestrial free air gravity anomalies (b) GOCE Tzz gravity gradient anomalies.

Table 2. The fitted covariance function parameters determined by surface data and GOCE Tzz gradient anomaly data, R_E is the mean radius of the Earth.

Description of Dataset	R_E-R_B (km)	Scale factor (a)	Varian ce ($mgal^2$)
Reduced surface free air gravity anomaly	-1.95	0.999	579.06
Reduced GOCE Tzz gradient anomaly	-0.13	0.859	794.65

These parameters are used as input for GEOCOL18 program of the GRAVSOFT package [4]. In addition, the observation error of the reduced Tzz and Txx gradient anomalies is set to 0.01 Eotvos.

The error estimates of the predicted reduced free air anomalies using covariance functions from surface free air gravity anomalies and GOCE Tzz gradient anomalies are shown in Fig.2 respectively. The errors using covariance function from GOCE Tzz gradients (Fig.2 (b)) shows a pattern correlated with the topography of the region. This may be potentially a result of a relatively smaller R_E-R_B (km) determined (Tab. 2) which needs further investigation.

After the prediction of reduced free air gravity anomalies, EGM08 to degree and order 60 is restored. Statistics of free-air gravity anomalies from terrestrial observations, LSC predictions using two different covariance functions, from second generation GOCE SH coefficients (M=250) based on time-wise (TIM) method are shown in Tab.1.

While the statistics of the direct comparison are shown in Tab.3, the statistics of the comparison after removing the Residual Terrain Model (RTM) effects from observed terrestrial free air gravity anomalies are given in Tab. 4.

Removal RTM effect improved the agreement at 20 % level. The use of the short-wavelength RTM reduction is appropriate for de-aliasing the selected sparse set of point surface gravity data. The RTM effects at GOCE altitude are nil.

Table 3. Statistics of differences between free-air gravity anomalies from LSC predictions using two different covariance functions and from second generation GOCE SH coefficients (M=250) based on time-wise (TIM) method and free-air gravity anomalies from terrestrial observations.

unit : mgal	mean	std.	min.	max.
LSC predicted (covariance from surface free air gravity anomalies)	-1.9	19.3	-185.2	120.2
LSC predicted (covariance from GOCE Tzz gradient anomalies)	-1.9	19.3	-183.9	120.3
GOCE TIM SH coefficients (M=250)	-1.7	18.7	-193.0	117.9

Table 4. Statistics of differences between free-air gravity anomalies from LSC predictions using two different covariance functions and from second generation GOCE SH coefficients (M=250) based on time-wise (TIM) method and free-air gravity anomalies from terrestrial observations (after Residual Terrain Model (RTM) effects are removed).

unit : mgal	mean	std.	min.	max.
LSC predicted (covariance from surface free air gravity anomalies)	-0.3	15.0	-75.2	99.6
LSC predicted (covariance from GOCE Tzz gradient anomalies)	- 0.3	14.9	-75.4	99.9
GOCE TIM SH coefficients (M=250)	-0.1	14.4	-78.3	112.7

After the removal of RTM effect, surface gravity anomalies are filtered by using 80 km full width Gaussian filter at GOCE resolution corresponding to degree and order 250 showing an agreement in the order of 7-8 mgal (Tab. 5). It is noteworthy to mention that the LSC prediction show a better agreement with the filtered RTM removed surface gravity anomalies than and those obtained from GOCE SH coefficients.

Table 5. Statistics of differences between free-air gravity anomalies from LSC predictions using two different covariance functions and from second generation GOCE SH coefficients (M=250) based on time-wise (TIM) method and free-air gravity anomalies from terrestrial observations (after Residual Terrain Model (RTM) effects are removed and a Gaussian low pass filter with 80 km full-width is applied).

unit : mgal	mean	std.	min.	max.
LSC predicted (covariance from surface free air gravity anomalies)	-0.3	7.8	-28.7	43.6
LSC predicted (covariance from GOCE Tzz gradient anomalies)	-0.3	7.6	-27.5	43.6
GOCE TIM SH coefficients (M=250)	-0.2	8.7	-28.7	40.9

We obtained the quasi-geoid model using GOCE TIM SH coefficients (M=250) at the same resolution as NKG-2004 quasi geoid model [6] and showed the differences between two models in Fig.3 after the mean difference between two models (0.31 m) are extracted. This mean difference is caused by difference in reference systems of the two quasi geoid models. The standard deviation between two geoid models is 29 cm and the differences are approximately in the order of 1 m in regions with rough topography due to short-wavelength gravity field variations which is not included in the GOCE derived quasi-geoid models.

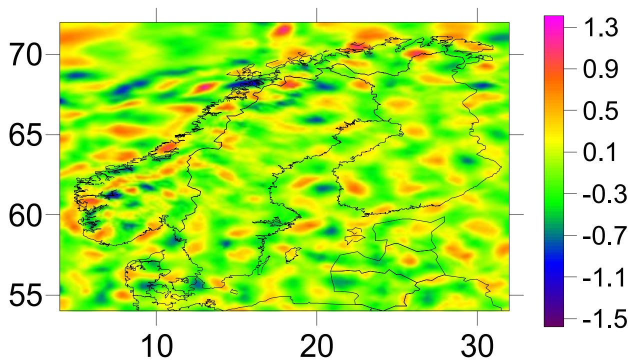

Figure 3. Difference (m) between NKG04 quasi-geoid heights and GOCE derived quasi-geoid heights using GOCE SH (M=250) based on time wise method.

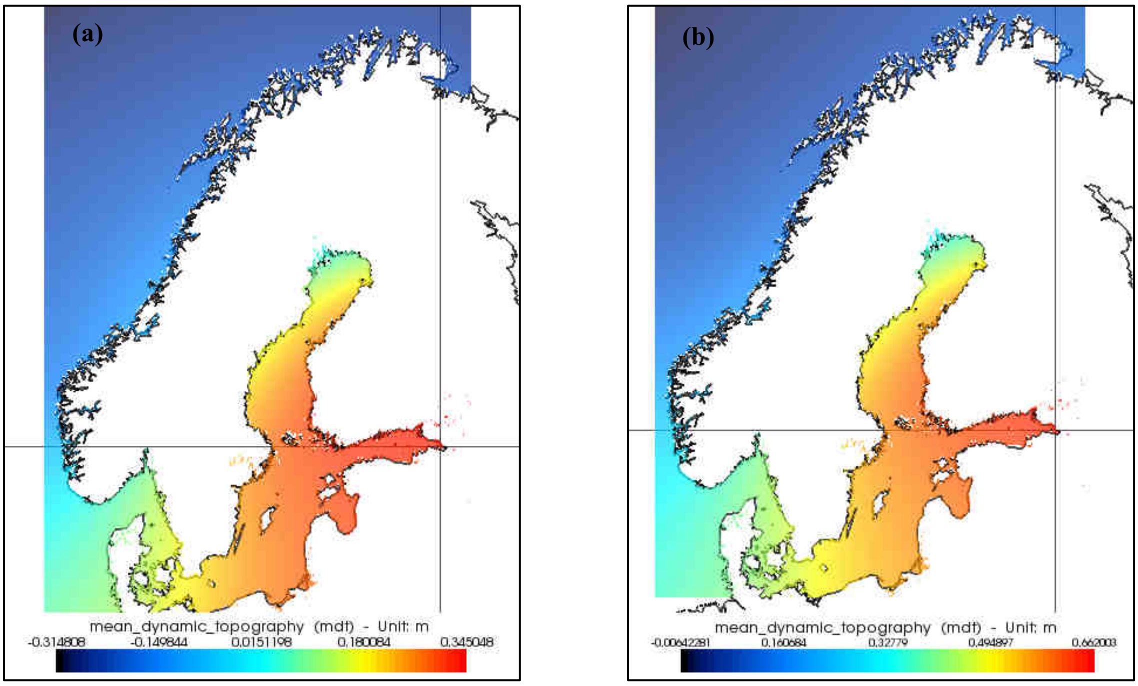

Figure 4. Mean Dynamic Topography of the Baltic Sea using DTU10 MSS model (a) NKG2004 quasi-geoid model (b) GOCE derived quasi-geoid model based on SH coefficients (M=250) of time-wise method

Finally, we compute the MDT model of the Baltic Sea using the NKG2004 quasi geoid and GOCE derived quasi geoid using DTU10 MSS model [1] and apply a Hanning filter with a cut length of 4° to remove the noise. The two MDT models are shown Fig. 4. When the mean difference between two quasi-geoid models (0.31 cm) is added to the NKG2004 geoid model derived MDT model, two MDT models agree quite well.

4. CONCLUSIONS

Using GOCE level-2 Tzz and Txx gravity gradients at satellite altitude in combination as input data, surface free air gravity anomalies over the Nordic region are predicted using Least Square Collocation with a direct comparison of 19 mgal level and much better (7-8 mgal) when surface data are filtered at the GOCE resolution.

Test of the performance of using covariance functions created separately from Tzz gradients and surface free air gravity anomalies to predict terrestrial gravity anomalies shows that the results are slightly dependent on the covariance function. However the error estimates from LSC using a covariance function created using GOCE Tzz gradient anomalies show a pattern correlated with the topography in the region. This may potentially be a result of a relatively smaller R_E-R_B (km) (Tab.2) which needs further investigation.

Combined with DTU10 Mean Sea Surface model, both the NKG-2004 quasi-geoid model of the Nordic and Baltic Area and the one obtained using second generation GOCE SH coefficients based on time-wise method can successfully reproduce the higher level of the Baltic Sea as compared to the Atlantic Ocean.

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